Rapid Prototyping at Zero Gravity for In-Flight Repairs and Fabrication on Space Station Freedom

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ABSTRACT

The ability to perform in-flight rapid prototyping would be of great benefit to NASA in two ways. First, repair parts could be fabricated from CAD designs beamed up from earth based laboratories which might allow a failed experiment to proceed. The mission specialists themselves, under the creative influence of space flight, might design a new part or tool and fabricate it on board in a matter of hours. Second, with metal casting and ceramic sintering facilities on board, rapid prototyping would allow manufacturing in space. This paper presents some test criteria for evaluating two of the rapid prototyping techniques, stereolithography and fused deposition, in microgravity conditions. Effects of the variation of head speed and strip width for the fused deposition process on the resulting mechanical properties are presented. The mechanical strength of the polyamide test bars increased with both increasing head speed and strip width. Increasing head speed would be desirable in microgravity applications.

INTRODUCTION

Goals and ambitions of the National Aeronautics and Space Administration for the exploration and development of space go hand in hand with advances in remote processing. Remote processing allows materials processing and component production to be performed in environments which are untenantable, or cost prohibitive using human labor. The separation of physical processing and the designer allows exploration and development activities to be immediately and practically supported by earthside manufacturing experts. The interest in solid freeform fabrication via rapid prototyping arises from its preeminence in the arena of remote processing technology. Especially relevant is the ability of remote processing technologies to immediately supply astronauts on the space station with tools and components. This advantage can hardly be understated. Tools which were not anticipated, or which fill too selective a niche to be stocked on the station could be readily supplied by ground transmission or supplied by a CD ROM on board library. This advantage, of course, applies to failed components which could be replaced on a temporary (awaiting resupply) basis.

Additionally remote processing would provide investigators the luxury of changing their design of an experiment on the space station during the course of their residence. If an inventive alteration occurred to a scientist while an experiment was being conducted on the space station, remote processing would allow new experimental parts to be designed and built while the experimenter was on station running the experiment. This would also apply to innovations developed by the astronauts during space station operations. New ideas and inventions could be investigated on an immediate trial basis.

Referencing the Lunar and Mars missions, remote processing technologies, using lunar regolith or martian simulant may be the only feasible means of materials supply for these enterprises.

The planned activities of Space Station Freedom include Life Science, Materials Science, Earth Science, and Astronomical Science experiments, but no manufacturing experiments (1). Each module on Space Station Freedom (SFF) contains racks for experiments with a volume of 35 cubic feet; the 3D Systems Model 250 Stereolithography Unit and the Statasys 3D Modeler Fused Deposition Unit would both fit in an SFF rack. One of the modules is a centrifuge, so that one gravity operation might be possible.

Before utilization on the Space Station, each rapid prototyping technique would have to be evaluated in microgravity in a series of preliminary modes. These modes are summarized in Table 1 to show the time available at zero gravity and the rapid prototyping result during such weightless times. The drop tower approach would not be feasible for the two rapid prototyping techniques considered here. Not enough of a part could be produced to be dimensioned, as only a portion of a single layer could be built in the 1-10 seconds available. Thus, model systems to simulate the behavior of the full unit would have to be employed. Liquid model systems are being evaluated in drop towers to evaluate surface tension effects in microgravity. Concus and Finn (2) report liquid to be stable in a round container, but to climb the corners of a square container. This would suggest modification of the present Stereolithography cubic liquid photopolymer vat to a cylindrical shape. The KC-135 flights using multiple 25 second weightless dives would be able to produce a small test part for dimensioning with a Rapid Prototyping unit on board. If the KC-135 tests were successful, a modified rapid prototyping unit could be sent on a Shuttle flight, where a full sized part could be built in microgravity. If the Shuttle experiments were successful, the relevant time factor on the Space Station for Rapid Prototyping would be driven by the Mission needs, since the Rapid Prototyping capability would be permanent.

PROCEDURE

The current test series is designed to determine processing parameters which impact strength and reliability of fused deposition modeled components. The material chosen was the current high strength material supplied by Stratasys Corporation, "plastic 300", a polyamide. Any component produced using fused deposition modeling differs from a bulk extruded polymer in the interfacial region between deposition strips. The number of interfaces, the construction of the interface, and the macroscopic and microscopic morphology of these interfaces will play a role in the mechanical behavior of the final part. We chose to initially look at the "road width" of the deposition strip, and the linear speed of the polymer extrusion head.

Fused deposition modeling uses the extrusion of a .050" diameter feed material filament through a melting chamber and into an extruder. The extrudate is then passed through a heated tip and, after swelling has been accounted for, lays down a deposition strip with a characteristic "road width". The extrusion head encompasses two degrees of freedom (X & Y) and the deposition platform rises and falls to produce the third (Z) degree of freedom.

Tensile test samples were produced with road widths of .030", .040", and .050". The linear speeds for the polymer extrusion head used were .400" per second, and .500" per second. The layer thickness or "Z slice" thickness in all cases was .015". The samples were produced with the strip orientation within the gauge length parallel to the direction of tensile stress.

The samples were tested according to ASTM D638-84 in the Marshall Space Flight Center Materials and Process Lab. Type Three specimens were fabricated as mentioned above. The temperature was 74°F and the relative humidity was 57% during the tests. The surface finish of all specimens was left in their original as produced form. The strain rate for all tests was 2 inches/minute. During the test there was not uniformity of strain behavior within the gauge length. The material in all cases underwent necking prior to failure, and in one case failure did not occur due to complete and uniform necking within the gauge length.

RESULTS AND DISCUSSION

There was a significant increase in stress at peak and stress at break over the increase from .040" strip width to .050" strip width. This occurred over same interval as the speed increase from .400"/second to .500"/second. The data shown in Figure 1 gives a good linear fit to the plots of the speed of the extruder tip vs. peak stress, 2% yield stress, and fracture stress. The correlation coefficients are in all cases equal to or above .996. On the other hand attempting to fit plots of the road width vs. the stresses with a linear fit results in no correlation coefficient higher than .756. The road width vs. stress plots all, however, are well fit by a 3rd order polynomial, as shown in Figure 2.

The mechanism of strength increase may be associated with a better linking between adjacent layers during sequential deposition. For an improvement in linking of two deposition strips two factors present themselves. First, a change in the polymer morphology present at the fusing edges may occur as a result of the change in the shear level of the deposited polymer. The change in shear level is due to increased pressure at the extrusion head, resulting in increased shear and an increase in the strip width. The second factor postulated is an increase in the temperature at which the fusion between strips takes place. An increase in fuse temperature could occur due to either a decrease in the cooling rate due to the increase in thermal mass from the wider strip width, or, a decrease in cooldown time between successive deposited strips due to increase speed of deposition.

CONCLUSIONS

The improvement in the polyamide mechanical properties with fused deposition head speed is encouraging for microgravity applications. Faster head speeds may be required to minimize distortions during the liquid extrusion phase of the fused deposition process.

REFERENCES

1. R. Moorehead, "Space Station Freedom Program and Operations," Meeting of the Wisconsin Space Business Round Table, Madison, Wisconsin, July 1992.

2. USRA Quarterly, Winter-Spring, 1992.

Table 1. Microgravity Test Modes for Rapid Prototyping

Test Mode	Time at Zero Gravity	Rapid Prototyping* Result During Test
DROP TOWER Small-Stairwell Large-Skyscraper	 1-2 seconds 5-10 seconds	 None-use model system None-use model system
KC-135 Flights	25 sec/dive, multiple dives	small part
Shuttle Flight	days	full sized part
Space Station Freedom	years	manufacturing

*Stereolithography = 10-20 sec/layer
Fused Deposition = 10 inches/sec

Fig. 1a

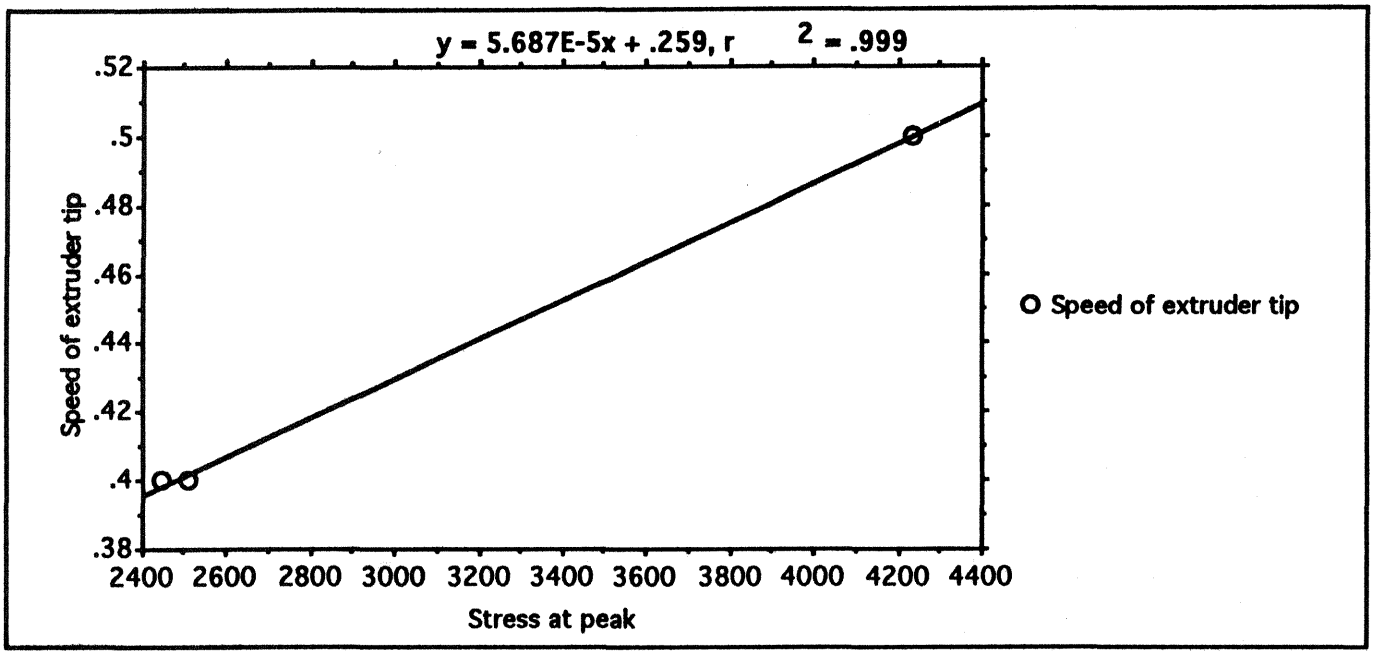

Fig. 1b

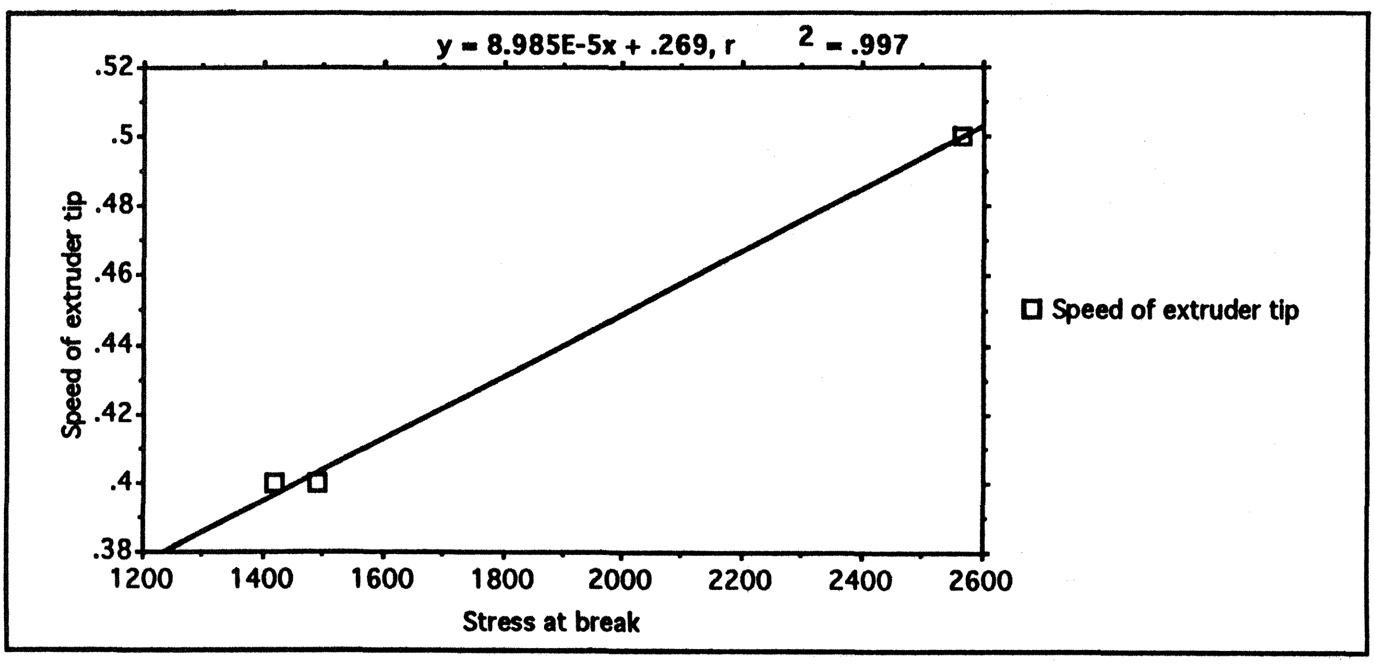

Figure 1. Variation of Polymer Strength with Fused Deposition Extruder Strip Speed

a. Peak Stress

b. Fracture Stress

c. 2% Yield Stress

Fig. 1c

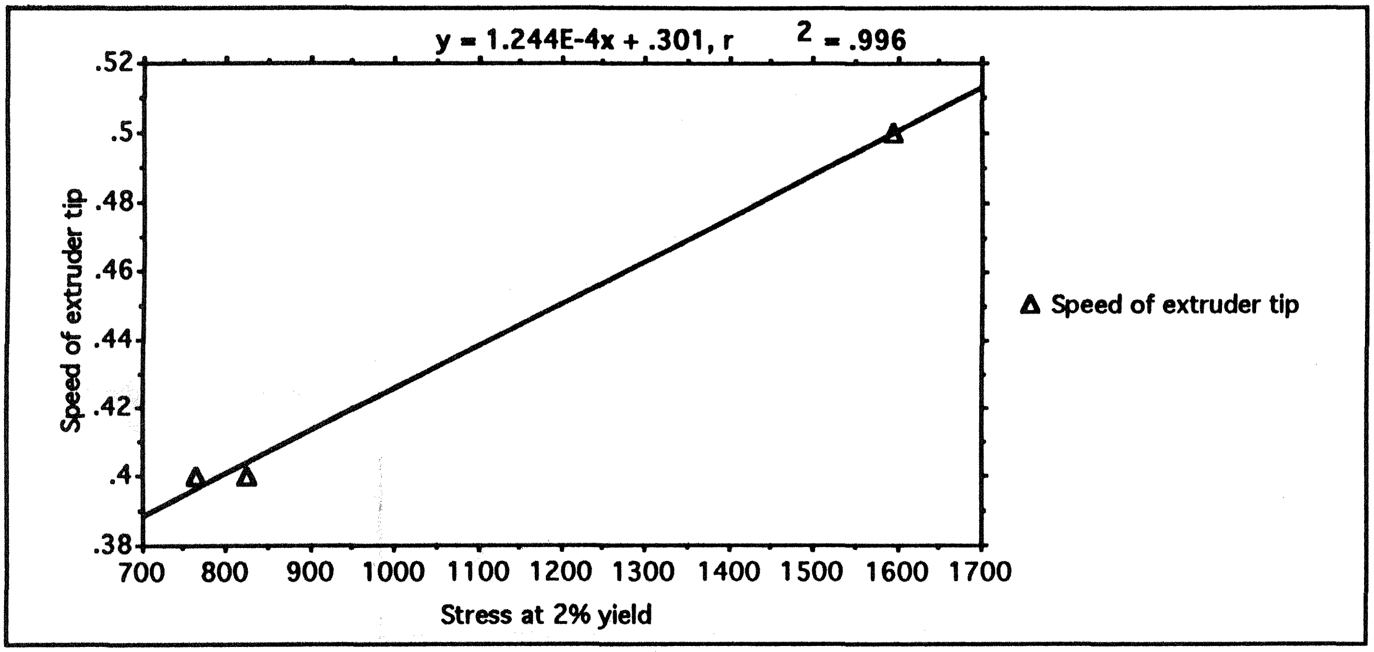
y = 1.244E-4x + .301, r 2 = .996
.52
.5
.48
.46
.44
.42
.4
.38
Speed of extruder tip
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
Stress at 2% yield
Δ Speed of extruder tip

Figure 2. Variation of Polymer Strength with Fused Deposition Road Width